II.A.1 Hydrogen Pathways Analysis for Polymer Electrolyte Membrane (PEM) Electrolysis

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Overall Objectives

- Analyze hydrogen production and delivery (P&D) pathways and provide case studies to DOE for enabling informed evaluation of the most economical, environmentally benign, and societally feasible paths for the P&D of hydrogen fuel for fuel cell vehicles (FCVs).
- Identify key "bottlenecks" to the success of these pathways, primary cost drivers, and remaining R&D challenges.
- Assess technical progress, benefits and limitations, levelized hydrogen costs, and potential to meet DOE P&D cost goals of $2 to $4 per gasoline gallon equivalent (gge) (dispensed, untaxed) by 2020.
- Provide analyses that assist DOE in setting research priorities.
- Apply the H2A Production Model as the primary analysis tool for projection of levelized hydrogen costs (U.S. dollars per kilogram of hydrogen [$/kg hydrogen]) and cost sensitivities.

Fiscal Year (FY) 2014 Objectives

- Develop a hydrogen pathway validation case based on hydrogen generation with grid-powered PEM electrolyzers.
- Select additional hydrogen pathways for analysis, gather information on those hydrogen pathways, and define those hydrogen pathways.
- Initiate a hydrogen pathway case based on hydrogen generation via dark fermentation of bio-feedstocks.
- Initiate a hydrogen pathway case based on hydrogen generation via high-temperature electrolysis using solid oxide electrolysis cells (SOECs).

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

Hydrogen Generation by Water Electrolysis

(F) Capital Cost

(G) System Efficiency and Electricity Cost

(K) Manufacturing

Dark Fermentative Hydrogen Production

(AX) Hydrogen Molar Yield

(AY) Feedstock Costs

(AZ) Systems Engineering

Technical Targets

This project conducts cost modeling to attain realistic cost estimates for the production and delivery of hydrogen fuel for FCVs. These values can help inform future technical targets.

- DOE P&D cost goals: $2 to $4/gge of hydrogen (dispensed, untaxed) by 2020

FY 2014 Accomplishments

- Completed a validation case for hydrogen generation with grid-powered, distributed and central, PEM electrolyzers using the H2A Production Model (Version 3) (Year 1, Milestone 2).
  - Developed PEM electrolysis case materials and supporting documentation and made them publicly available and downloadable from the website: http://www.hydrogen.energy.gov/h2a_prod_studies.html
  - Developed four PEM electrolysis public cases that reflect a $4/kg to $5/kg hydrogen production cost, based on an average cost of electricity of 6.1¢ to

6.9¢/kWh. Found electricity costs to be the primary cost driver.
    - Quantitatively demonstrated that the three main cost drivers for the levelized hydrogen cost from PEM electrolysis are (1) electricity price, (2) electrolyzer electrical efficiency, and (3) electrolyzer capital cost.
    - Described the PEM electrolysis capital cost breakdown in detail, which is a unique contribution of this work.
- Initiated hydrogen pathway cases based on hydrogen generation from dark fermentation of biomass.
    - Developed a questionnaire to solicit case parameter information from industry and researcher experts.
    - Distributed questionnaire and collected data.
- Initiated hydrogen pathway cases based on hydrogen generation from SOEC.
    - Developed a questionnaire to solicit case parameter information from industry and researcher experts.
    - Distributed questionnaire and collected data.

INTRODUCTION

This report reflects work conducted in the first year of a three-year project to analyze innovative hydrogen production and delivery pathways and their potential to meet the DOE P&D cost goal of \$2/gge to \$4/gge by 2020. To date, work has concentrated on a validation case based on PEM electrolysis technology. The purpose of the validation case is to demonstrate the successful application of the analysis procedure to a near-term technology for which some measure of information is known and against which modeling results can be compared. After validation, the analysis methodology can be applied to less developed technologies with greater confidence in the results. The analysis methodology utilizes DOE's H2A Distributed and Central Hydrogen Production models.[1] Those models provide a transparent modeling framework and apply standard mass, energy, and economic analysis methods agreed upon by DOE's Hydrogen and Fuel Cells Program.

APPROACH

The following approach was applied to the PEM electrolysis case study and is the model for future analyses:

- Conduct literature review
- Develop, circulate, and analyze results from an industry questionnaire covering the targeted technology (i.e., PEM electrolysis)
- Define generalized cases for systems of different sizes and technology readiness levels (TRLs)
- Run H2A models with general case input data to calculate the levelized cost of hydrogen (\$/kg hydrogen)
- Perform sensitivity analyses (including tornado and waterfall charts) to identify key cost drivers
- Document case study results
- Vet case study results with DOE, industry, and team partners
- Repeat these steps until agreement is attained among project partners

A questionnaire spreadsheet was circulated to four electrolyzer companies (Giner Inc., Hydrogenics Inc., ITM Power LLC, and Proton Onsite Inc.) to gather data on PEM electrolyzer performance. Collected data included H2A model input parameters necessary for developing cases and covered engineering system definition, stack and balance-of-plant (BOP) capital costs, and other economic factors. The research team analyzed this data and used it to synthesize generalized cases, so as not to reveal any one company's sensitive technical information. Four public generalized cases were developed.

- Current Forecourt
- Current Central
- Future Forecourt
- Future Central

Data from the four generalized cases were used to populate the H2A Model (Version 3.0) and to generate estimates of the levelized hydrogen cost. The four eletrolyzer companies vetted the generalized cases, H2A model results, sensitivity limit parameters and results, and resulting documentation.

Two hydrogen production plant sizes are considered: Forecourt[2] at 1,500 kg hydrogen/day and Central at 50,000 kg hydrogen/day. Two technology development time horizons are considered: Current for year 2013 TRL and Future for year 2025 TRL. Current cases assume a short-term technology readiness projection from technology that has been demonstrated already in the lab. Future cases project the development of the technology with better materials, capabilities, efficiencies, lifetimes, and costs than that currently demonstrated. A fifth non-public case was also developed based on existing PEM electrolyzer TRL performance (i.e., using commercially available products). However, results are not disclosed due to corporate sensitivities.

[1] http://www.hydrogen.energy.gov/h2a_analysis.html

[2] Hydrogen production cost is the focus of the case study. For the Forecourt cases, compression, storage, and dispensing computations are included in the base H2A spreadsheet, and thus they are also reported in the case study.

Analyses were also initiated for hydrogen production via dark fermentation and high temperature SOEC. The dark fermentation case study considers three types of biomass feedstock, an energy crop (e.g., corn stover), a waste stream (e.g., agricultural waste), and a refined bioproduct (e.g., alcohol or sugar). For both analyses, the team conducted a literature review, cultivated a list of experts to serve as questionnaire respondents (including the European Institute for Energy Research for the SOEC analysis), created a detailed techno-economic questionnaire, revised the questionnaire in response to expert technical feedback from DOE and from the Idaho National Laboratory (INL) for the SOEC analysis, circulated the questionnaire to the list of experts, pursued non-disclosure agreements at the request of experts, and collected initial questionnaire responses from several entities. Draft case studies are in the process of being created but analysis results are not yet available.

RESULTS

Figure 1 shows the cost results for the four public H2A Production PEM electrolysis cases. The y-axis shows the levelized cost of producing hydrogen and the cost breakdown. All cases reflect a $4/kg to $5/kg hydrogen production cost, based on an average cost of electricity of 6.1¢/kWh to 6.9¢/kWh. The primary cost driver is the feedstock cost, which is mainly the cost of electricity expenditures for operation of the PEM stack[3]. These feedstock costs can be reduced through either lower electricity prices or higher electrolyzer efficiencies. The second most important cost driver is the electrolyzer equipment capital cost, which includes the costs of the stack and associated BOP. The figure also shows that the reduction in hydrogen cost is estimated to be larger in moving from a Current to a Future case, compared with moving from a Forecourt to a Central case. Although the data is not shown publicly for the Existing case, it is important to note that large capital cost reductions are predicted between Existing and Current systems, and between Current and Future systems. The vertical bars at the top of the figure reflect the low and high projections based solely on low and high sensitivity limits for uninstalled capital costs (including stack and BOP costs) that were agreed upon by industry. Also, in addition to the levelized hydrogen production cost shown on the y-axis, the cost of compression, storage, and dispensing is expected to add between 37% and 47% in the Forecourt cases.

A unique contribution of this work is the detailed capital cost breakdown, which is shown for the Current Forecourt Case in Figure 2. The stack constitutes ~41% of system capital cost, and is the primary cost driver for system capital costs in all cases. For the Current Forecourt Case, ~60% of the stack capital costs can be attributed to the combined costs of the membrane, catalyst, anode, and cathode.

Figures 3 and 4 show waterfall charts for the Forecourt and Central cases. The waterfall charts graphically show the cumulative change in hydrogen production cost on the y-axis corresponding to each change in input parameter on the x-axis in moving from the Current case on the left to the Future case on the right. The charts show that the increase in electricity price expected over time is expected to be

[3] Water is technically the only feedstock. However, electricity is tabulated under feedstock cost, and not utility cost, to match past analyses.

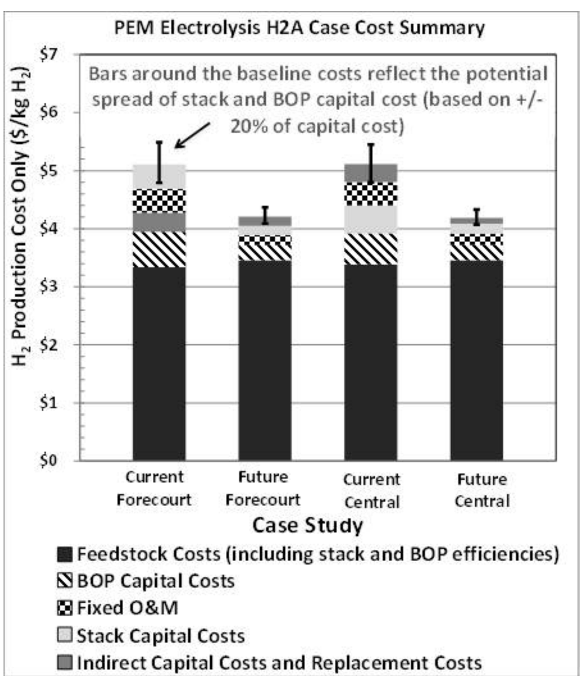

FIGURE 1. H2A Production PEM Electrolysis Breakdown (cost results reported in 2007$; average electricity prices for all cases range between 6.1 cents/kWh and 6.9 cents/kWh)

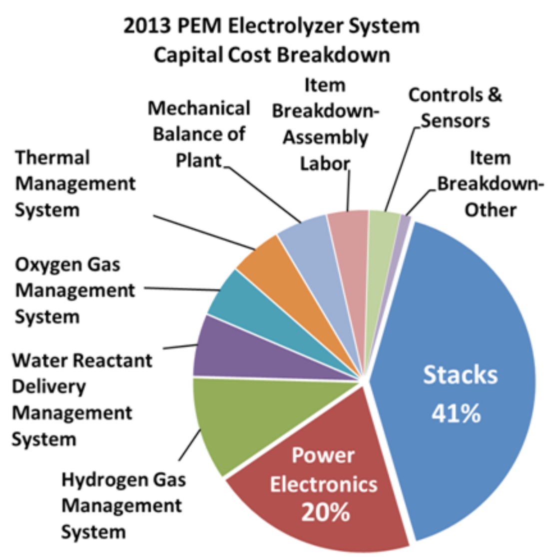

FIGURE 2. Capital Cost Breakdown for Current Forecourt Case

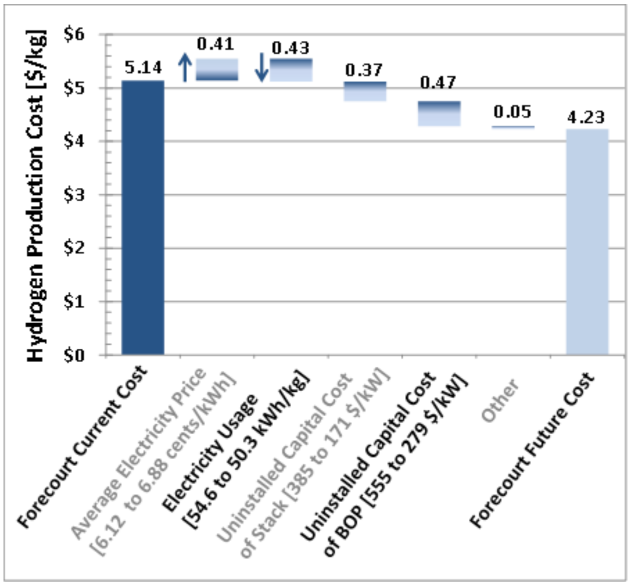

FIGURE 3. Waterfall Chart for the Forecourt Case

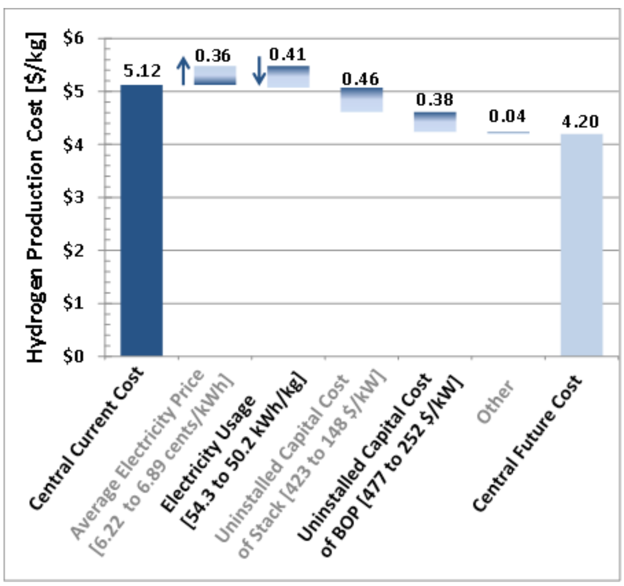

FIGURE 4. Waterfall Chart for the Central Case

counteracted by the increase in electrical efficiency of the electrolyzer stack over time. Because the model's electricity prices follow the Annual Energy Outlook projections, which vary by year, and because the Current and Future cases cover different timespans, an increase in electricity price is expected between Current and Future cases, and therefore electricity expenditures increase, as shown in the chart's second column from the left. At the same time, the increase in electrical efficiency expected in the future reduces net electricity expenditures and brings down the hydrogen production cost. This counteractive effect is shown in the third column from the left in each chart.

All of the case studies correspond to futuristic scenarios since PEM electrolyzer are not currently mass-produced. Consequently, direct comparisons between case study results here and existing system costs do not constitute an apples-to-apples comparison. However, to the extent possible, the methodology, input variables, and results for the PEM electrolyzer were vetted by the four electrolyzer companies, judged to be reasonable, and thus informally validated for purposes of application to future case studies.

CONCLUSIONS AND FUTURE DIRECTIONS

In its first year, this project made key observations and important achievements.

- A Validation Case was completed for hydrogen generation with grid-powered PEM electrolyzers using the H2A Production Model (V3).
- Four PEM electrolysis companies were asked to fill out questionnaires inquiring about engineering and economic information for PEM electrolyzers, and five generalized cases were developed (four public, one non-public).
- Large capital cost reductions are predicted between Existing and Current systems, and between Current and Future systems.
- All PEM Electrolysis cases reflect a $4/kg to $5/kg hydrogen production cost, based on an average cost of electricity of 6.1¢ to 6.9¢/kWh. Electricity costs are the primary cost driver.
- The hydrogen cost reduction is greater in moving from a Current to a Future case, compared with moving from a Forecourt to a Central case.
- The three main cost drivers for the levelized hydrogen cost are (1) electricity price, (2) electrolyzer electrical efficiency, and (3) electrolyzer capital cost.
- A unique contribution of this work is the detailed capital cost breakdown.
- Compression, storage and dispensing costs are expected to add ~37% to ~47% to the levelized hydrogen production cost in the Forecourt Cases.
- Analysis of dark fermentation of biomass and SOEC electrolysis was initiated. Results are not yet available.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Hydrogen and Fuel Cells Program Award. Awarded to Brian D. James by the Director of the Fuel Cell Technologies Office, Sunita Satyapal, June 17th 2014.

FY 2014 PUBLICATIONS/PRESENTATIONS

Web-Posted PEM Electrolysis Case Studies and Supporting Documentation

H2A Production Version 3 Excel Models: http://www.hydrogen.energy.gov/h2a_prod_studies.html

- *Central Electrolysis*
  - Current Central Hydrogen Production from PEM Electrolysis Version 3.0
  - Future Central Hydrogen Production from PEM Electrolysis Version 3.0
- Forecourt (Distributed) Electrolysis
  - Current Forecourt Hydrogen Production from PEM Electrolysis Version 3.0
  - Future Forecourt Hydrogen Production from PEM Electrolysis Version 3.0

Supporting Documentation

- Report: James, B.D., Colella, W.G., Moton, J.M., Saur, G., Ramsden, T.G., *PEM Electrolysis H2A Production Case Study Documentation*, report for the U.S. DOE EERE FCT program, December 2013: http://www.hydrogen.energy.gov/pdfs/h2a_pem_electrolysis_case_study_documentation.pdf
- Slide presentation: Colella, W.G., James, B.D., Moton, J.M., "Hydrogen Pathways Analysis for Polymer Electrolyte Membrane (PEM) Electrolysis," *2014 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting*, Washington, D.C., June 16th-20th, 2014. http://www.hydrogen.energy.gov/pdfs/review14/pd102_james_2014_o.pdf
- DOE program record, http://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

Peer-Reviewed Journal Articles and Conference Proceedings

1. Colella, W. G., James, B. D., Moton, J. M., Saur, G., Ramsden, T., "Next Generation Hydrogen Production Systems Using Proton Exchange Membrane Electrolysis," *Proceedings of the ASME 2014 12th Fuel Cell Science, Engineering and Technology Conference*, June 30th-July 2nd, 2014, Boston, Massachusetts, USA, ESFuelCell2014-6649.

2. Colella, W.G., Moton, J.M., James, B.D. "Techno-Economic Analysis of Advanced Approaches for Generating Hydrogen Fuel for Vehicles," *Proceedings of the Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-180).

3. Colella, W.G., "Reducing Energy, Environmental, and Economic Constraints in Global Transport Supply Chains with Novel Fuel Cell and Hydrogen Technologies," *Proceedings of the Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-178).

4. Colella, W.G. "Resolving Constraints in Global Energy Supply with Cogenerative, Polygenerative, and Fast Ramping Fuel Cells," *Proceedings of the Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-177).

Peer-Reviewed Reports

1. James, B. D., Colella, W. G., Moton, J. M., Saur, G., Ramsden, T., *PEM Electrolysis H2A Production Case Study Documentation*, report for the U.S. DOE EERE FCT program, Revised and Publicly Re-Released June 2014.

2. James, B. D., Colella, W. G., Moton, J. M., Saur, G., Ramsden, T., *ADDENDUM to the PEM Electrolysis H2A Production Case Study Documentation*, report for the U.S. DOE EERE FCT program, Revised and Re-Submitted June 2014.

Plenary Oral Conference Presentations

1. Colella, W.G., James, B.D., Moton, J.M., Saur, G., Ramsden, T.G., "Techno-economic Analysis of PEM Electrolysis," *Electrolytic Hydrogen Production Workshop*, U.S. DOE EERE FCT Office and the National Renewable Energy Laboratory (NREL), Golden, Colorado, Feb. 27th-28th, 2014.

Oral Conference Presentations

1. Colella, W.G., James, B. D., Moton, J.M., "Hydrogen Pathways Analysis for Polymer Electrolyte Membrane (PEM) Electrolysis," *2014 DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting*, Washington, D.C., June 16th-20th, 2014.

2. Colella, W.G., Moton, J.M., James, B.D. "Techno-Economic Analysis of Advanced Approaches for Generating Hydrogen Fuel for Vehicles," *Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-180).

3. Colella, W.G., "Reducing Energy, Environmental, and Economic Constraints in Global Transport Supply Chains with Novel Fuel Cell and Hydrogen Technologies," *Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-178).

4. Colella, W.G., James, B.D., Spisak, A.B., Moton, J.M., "Next Generation Electrochemical Systems," *American Institute of Chemical Engineers (AIChE) Annual Meeting*, San Francisco, CA, Nov. 3th-8th, 2013.

5. Colella, W.G., Moton, J.M., James, B.D., "Analysis of Emerging Hydrogen Production and Delivery Pathways," *2013 Fuel Cell Seminar*, Session STA33 Hydrogen Production & Storage, Paper Number 266, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.

Invited Talks

1. Colella, W.G., James, B.D., Moton, J.M., Saur, G., Ramsden, T.G., "Thermo-economic Analysis of Producing Hydrogen with Proton Exchange Membrane Electrolyzers," *International Energy Agency (IEA) Advanced Fuel Cells Annex 25 Meeting No 10*, SOFC-POWER Inc. premises in Trento, Italy, April 23rd-24th 2014 (delivered remotely via webinar.)

2. James, B. D., Colella, W. G., Moton, J. M., Saur, G., Ramsden, T., *Techno-Economic Analysis of Hydrogen Production by PEM Electrolysis,* Hydrogen Production Technical Team (HPTT) Meeting, delivered remotely from Arlington, VA, Dec. 3rd, 2013.

3. James, B. D., Colella, W. G., Moton, J. M., *Techno-Economic Analysis of Hydrogen Production Pathways,* DOE Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) Meeting, NREL, Golden, Colorado, delivered remotely from Arlington, VA, Oct. 30th, 2013.

4. James, B. D., Colella, W. G., Moton, J. M., Saur, G., Ramsden, T., "Analysis of Hydrogen Costs from Proton Exchange Membrane (PEM) Electrolyzers." Presentation to the U.S. Department of Energy Office of Energy Efficiency & Renewable Energy Fuel Cell Technologies Program, Washington, D.C., September 27th, 2013.

Poster Presentations

1. Colella, W.G., "Reducing Energy, Environmental, and Economic Constraints in Global Transport Supply Chains with Novel Fuel Cell and Hydrogen Technologies," *Fifth European Fuel Cell Technology & Applications Conference - Piero Lunghi Conference and Exhibition (EFC2013)*, Rome, Italy, Dec. 11th-13th, 2013 (EFC13-178).

2. Colella, W.G., Moton, J.M., James, B.D., "Analysis of Emerging Hydrogen Production and Delivery Pathways," *2013 Fuel Cell Seminar*, Session STA33 Hydrogen Production & Storage, Paper Number 266, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.

3. Colella, W.G., "Resolving Bottlenecks in Transportation Supply Chains with Next Generation Fuel Cell and Hydrogen Energy Systems," *2013 Fuel Cell Seminar*, Greater Columbus Convention Center, Columbus, Ohio, October 21st-24th, 2013.